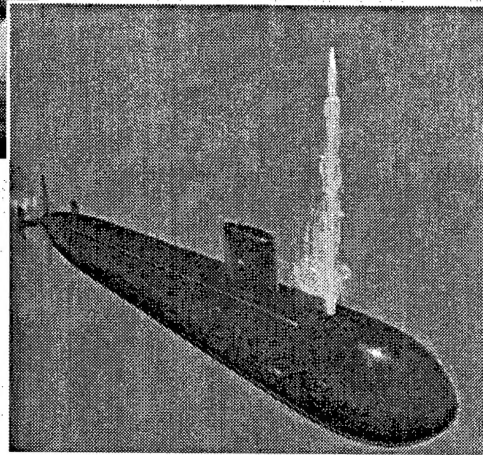
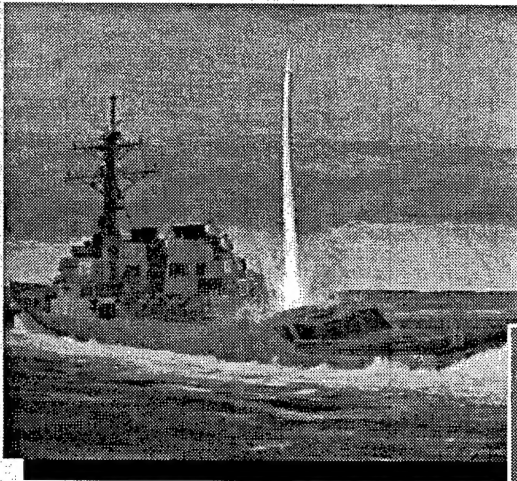
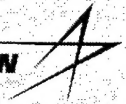


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Adaptation of the Army Tactical Missile System to Undersea Operations

2 December 1996

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30 August 1996

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ADAPTATION OF THE ARMY TACTICAL MISSILE SYSTEM TO UNDERSEA OPERATIONS

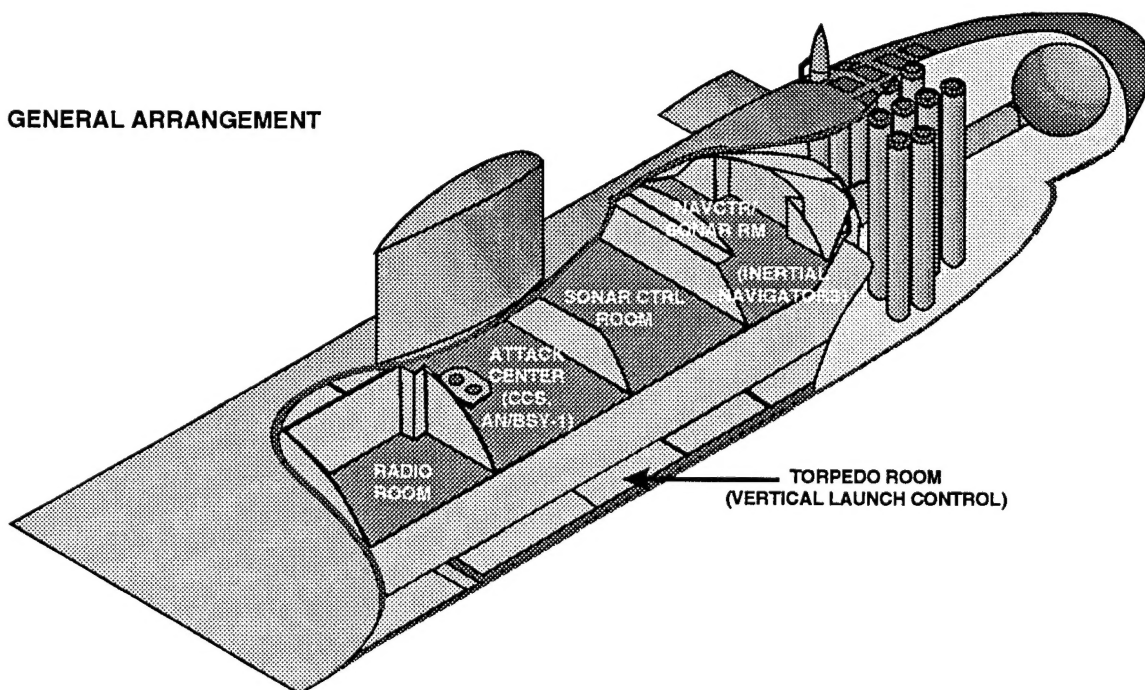
INTRODUCTION

The USN Strategic System Program Office authorized a study in 1995 to evaluate the launch of tactical battlefield ballistic missile from the 688I fast attack submarine. The missile evaluated was the Army's Tactical Missile System (ATACMS), MGM-140A. The choice was based on the production status and combat history of the missile system. The range and payload of ATACMS made it ideal for fire support from the sea. The Los Angeles class submarine was selected as the launch platform. These fast attack subs provide 12 launch cells that dimensionally allow the installation of ATACMS missiles stored in capsules with self-contained undersea cold launch capability. Figure 1 locates the launch cells in the 688 class hull.

A Sea-Launched TACMS (SLATACMS) missile is a derivative of the Army Block IA missile with changes to accommodate the dimensional constraints of the launch capsule. The changes are required for physical fit within the submarine VLS capsule to be compatible with the submarine environments, and existing submarine systems without changing them; and to allow for different launch and flight conditions.

The SLATACMS will be 199.0" long, while the Block IA missile is 156.5" long. The added length is the result of a longer boattail that allows the fins to be folded within a smaller envelope and the addition of fin module behind the boattail for stability during underwater flight. The fin module is jettisoned after broach and before missile motor ignition, resulting in a flight

GENERAL ARRANGEMENT



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FIGURE 1. SLATACMS SYSTEMS INTEGRATION

missile length of 170.13". The missile diameter and nose shape will remain the same as Block IA (23.9" dia. and 3.07:1 VK). Figure 2 illustrates the configuration.

CAPSULE CONSIDERATIONS

The capsule design is dominated by three requirements: submarine integration, weapon-induced (near miss) shock, and missile exit velocity. The study results in each of these areas are outlined below.

Submarine Integration

The SLATACMS is mechanically integrated with the SSN 688 class submarine by installing the combined missile and launch capsule as an all-up-around (AUR), into a vertical missile tube in the forward main ballast tank. These tubes were designed for the Tomahawk missile. Although the SLATACMS AUR poses several distinct requirements, the installation is sufficiently similar to that of the Tomahawk to provide a significant background of design information.

Although the SLATACMS missile has a similar mass to the Tomahawk, the diameter is larger and is shorter in length. These dimensional differences decrease the radial clearances and result in a significant length of unused missile tube. A schematic of the preferred location of the SLATACMS AUR in the submarine vertical launch tube is shown in Figure 3. This position near the top of the missile tube results in a higher center of gravity for the installation than was the case for the Tomahawk. The effect of this higher center of gravity on the submarine roll stability was evaluated. The results of that evaluation, shown in Figure 4, indicated that the weight/cg combination of the SLATACMS AUR installation is within the acceptable envelope for the submarine.

Because of the increased missile diameter, the SLATACMS AUR capsule clearance between the capsule tube and the capsule support flange is a minimum of 0.03". As a result, the SLATACMS AUR installation approach differs from the Tomahawk approach in two ways. First,

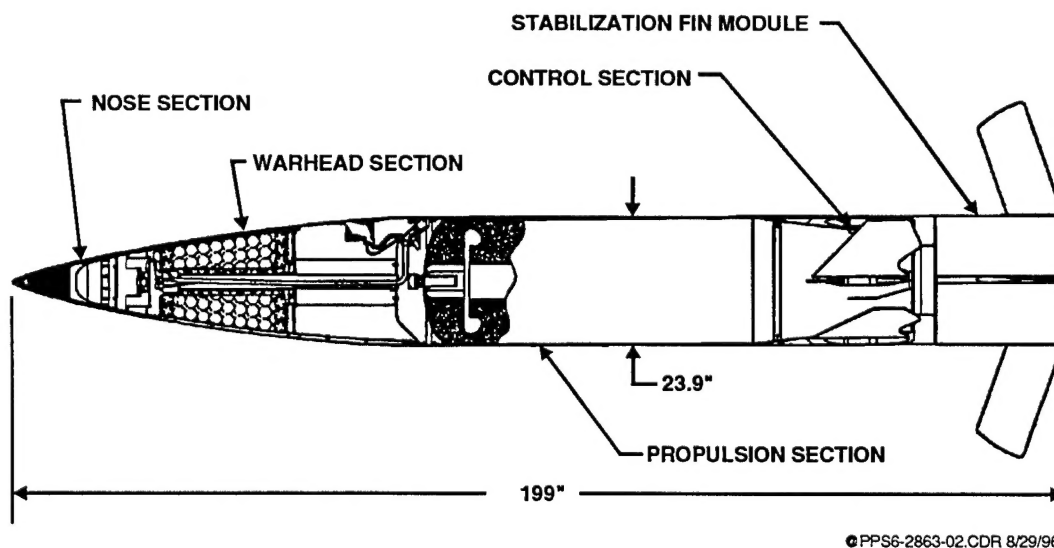
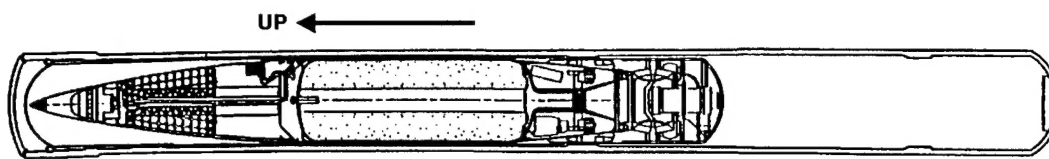


FIGURE 2. SLATACMS MISSILE CONFIGURATION

the capsule umbilical is routed inside the capsule itself. Special consideration was given to the design characteristics of the launch support pads, because of the clearances involved. After a parametric study of potential pad designs, a low profile pad design with linear force deflection characteristics was selected. An inboard profile of the SLATACMS AUR is shown in Figure 5.

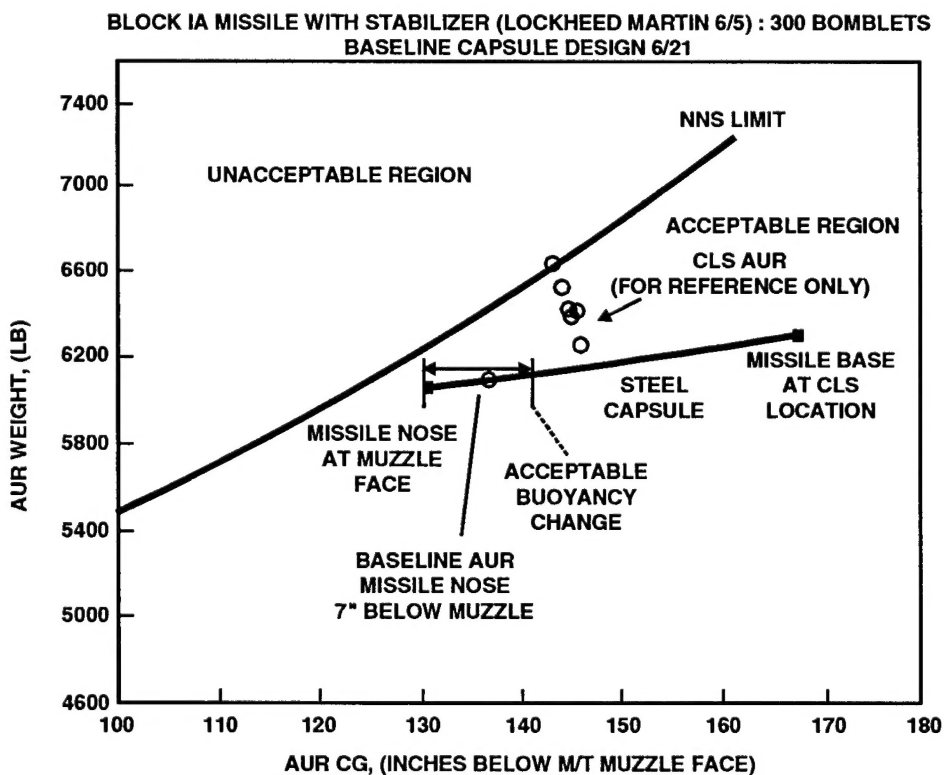
Weapon-Induced (Near Miss) Shock

The shock motions assumed for this study were derived from the Submerged Shock Test Vehicle (SSTV) tests which were conducted at San Clemente Island in 1983. During the test, the SSTV experienced a displacement of 1" in 25 milliseconds. This movement was



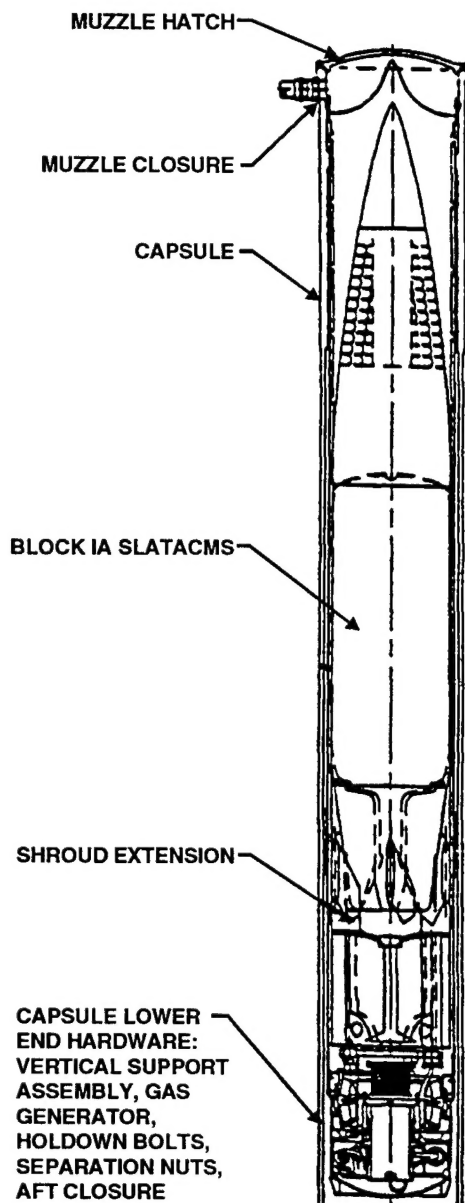
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FIGURE 3. TACMS IN 688 CLASS SUBMARINE VLS TUBE



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FIGURE 4. AUR WEIGHT AND CG REQUIREMENTS



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FIGURE 5. CAPSULE ASSEMBLY

assumed to represent missile tube motion as the result of a near miss. Because of the available distances between either the capsule and the missile tube (0.29") or the missile and the capsule (0.66"), the missile cannot be fully isolated from the tube motion. The failure to completely isolate the missile from the imposed motion will mean that shock loads will be transferred

to the missile. However, because of its ATACMS heritage, the SLATACMS structure was designed to withstand significant shock loads. To see if the SLATACMS missile has sufficient design margin to handle the shock loads produced by the imposed tube motion, Westinghouse Electric Corporation (WEC) developed the computer model outlined in Figure 6.

As illustrated in Figure 6, the capsule is assumed to be rigidly attached to the top of the missile tube and to be laterally supported by a set of interface pads somewhere along the length of the capsule. These interface pads are assumed to have a linear force deflection characteristic. The missile is supported laterally within the capsule by a distributed set of shock pads which are attached to the capsule. These shock pads are assumed to have a plateau force deflection characteristic. The principal design variables studied were:

1. Lower capsule geometry (neck down aft of missile base)
2. Interface pad stiffness and location
3. Shock pad stiffness and distribution

Several designs were considered. The chosen design has comparatively stiff interface pads mounted to the missile tube at the middle shock land. There were 44 shock pads arranged in 11 rows of four pads each. The lower six rows support the missile in the stowed position and have a plateau level of 65 psi. (The upper five rows, which are not required to support the missile during the near miss analysis, have a plateau level of 20 psi set by launch considerations.) The analysis indicates that, with the chosen capsule design, the SLATACMS AUR will survive the shock loads resulting from a near miss with a margin of

1.5 over allowables, which are derived from ultimate capabilities with a factor of safety of 1.25.

Missile Exit Velocity

The gas generator design constraints are the missile exit velocity, the missile loads (pressure and acceleration), and the gas pressure at missile base exit (uncorking pressure). Because the mass of the SLATACMS and required exit velocity are similar to those of the Tomahawk, the energy requirements of the two gas generators are about the same.

Consequently, the mass/volume characteristics of the propellant grain should be such that much of the Tomahawk gas generator hardware could be used. The propellant grain itself, however, will require modification.

Since the missile base will exit the capsule in a body length and the exit velocity

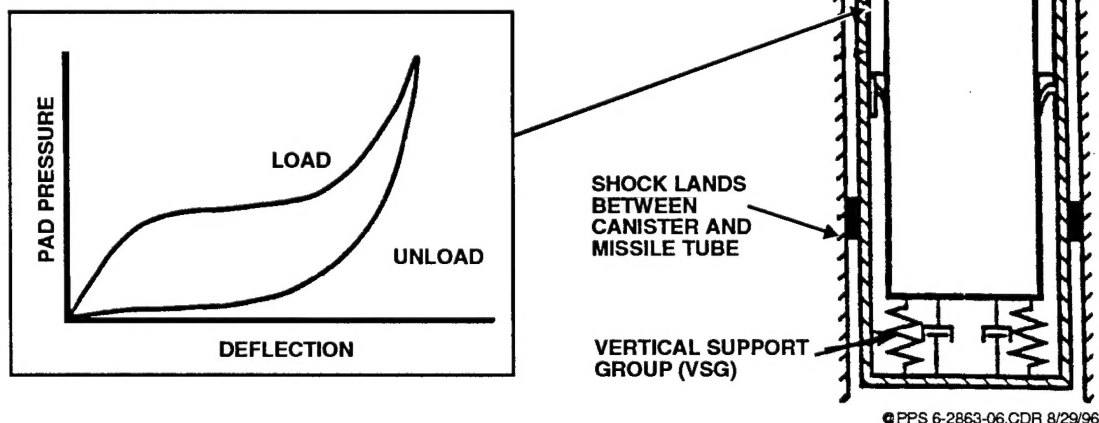


FIGURE 6. SIXTUBE SHOCK MODEL SCHEMATIC FOR SLATACMS

requirements are about the same, the shorter SLATACMS missile will require an increase in the average acceleration (average capsule pressure) operating over a shorter period of time. To prevent damage to the submarine, the uncorking pressure

must be less than a specified level (assumed to be 40 psid). To achieve this pressure level, the burn of the propellant must be essentially complete at base exit; therefore, the propellant grain burn time must be decreased. The gas flow rate

required to maintain the higher capsule pressure in the expanding volume below the missile must be increased because the SLATACMS being larger in diameter.

WEC, with the assistance of Alliant Techsystems, analyzed several potential solutions to the SLATACMS gas generator grain requirements. The study result was a modified grain with an initial burn surface to volume ratio, which is higher than that used for the Tomahawk grain. The capsule pressure time histories of the proposed grain configuration for various launch depths are shown in Figure 7. The resulting exit velocities are compared to the assumed exit velocity requirements in Figure 8. The result is that the design of a

satisfactory gas generator is considered feasible.

Missile and missile components include air paths to allow for pre-launch pressurization and decompression during capsule ejection. The inertial navigation system would have pressure ports added to it to compensate for the high (~100 psig) pre-launch pressures. Internal components withstand the overpressure environment. Due to humidity, long term storage of the vented INS chassis would be a concern. The launch capsule would have no breather valve so humidity is easier to control during storage. The air available for pressurization from the submarine is dry (dew point -30°F), precluding moisture

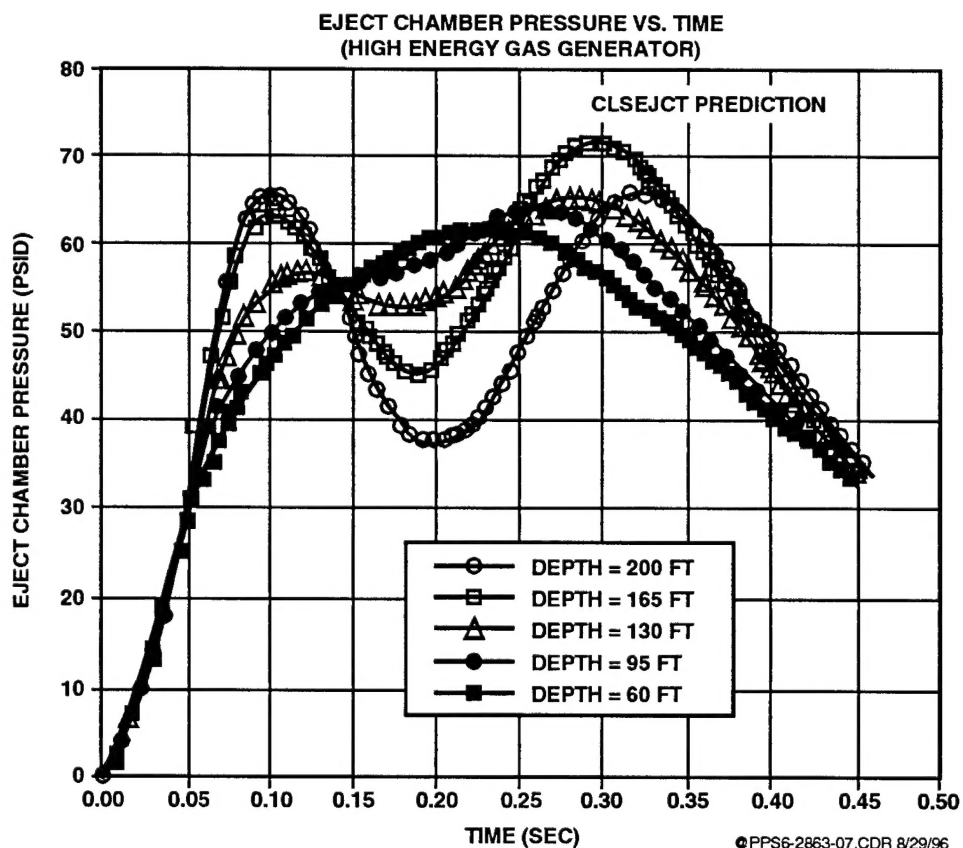
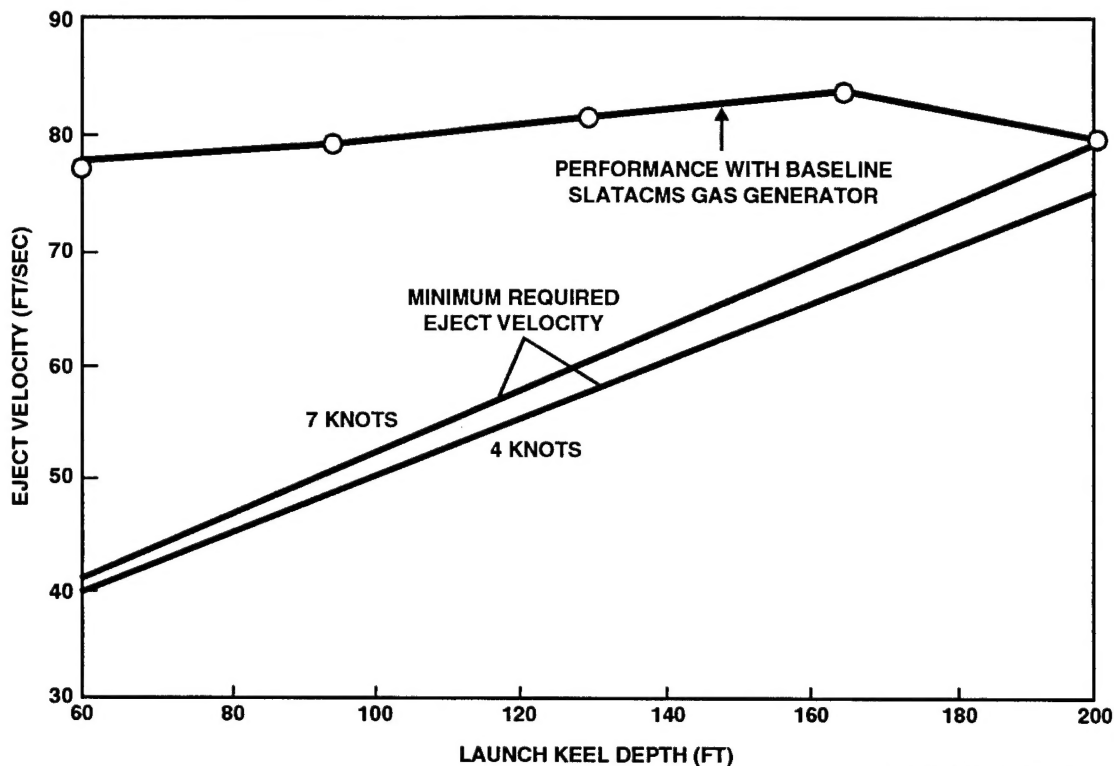


FIGURE 7. LAUNCH EJECT CHAMBER PRESSURE WITH BASELINE SLATACMS GAS GENERATOR



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FIGURE 8. EJECT VELOCITY PERFORMANCE REQUIREMENT

build up, once the missile is in the submarine.

The principal munition delivered by the missile is the M74 fragmentation grenade. The warhead housing the grenade is identical to the Army missile. Warhead skins are pyrotechnically cut on command from the inertial navigation system through an electronic safe and arm fuze. The closure surface between the forward bulkhead and warhead skin contain venting relief to the internal structure and components — pressure ports, grenade locations, fuze and GPS antenna (shown in Figure 9).

The propulsion section uses the Block 1A motor as the baseline with the following changes: the ignitor moves from the nozzle throat to the forward end of the motor case, a blast tube is added between the aft dome and nozzle, and the nozzle is

adapted to interface with the blast tube. Propulsion general arrangement is shown in Figure 10.

The control section structure is extended to accommodate the new control surfaces and blast tube. The structure length is increased by about 13.6" for a total length of 26.07" and the exterior angle is altered to 6°. These changes allow space for the fins to fold within the capsule envelope. A flange is added to the aft face to interface with the stabilization module. The longitudinal loads during shipping and vertical loads during deployment in a submarine are transferred through this mounting ring. Control electronics are modified to allow the housing to vent the pressure internally. The batteries and electromechanical actuators can stand the over-pressure and have no change.

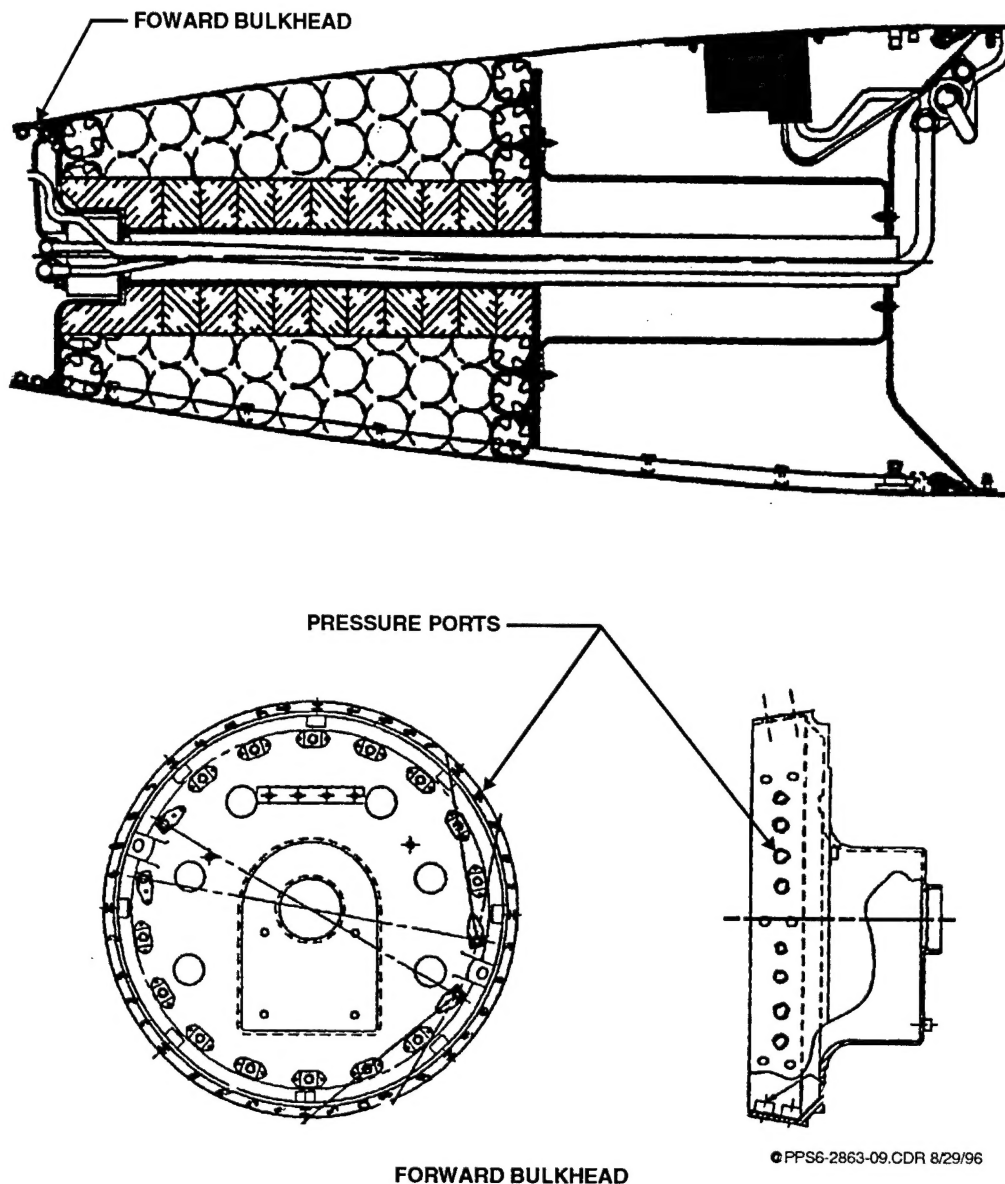


FIGURE 9. WARHEAD SECTION

MISSILE UNDERWATER FLIGHT

In addition to the normal stability considerations, underwater flight poses a number of considerations not encountered in atmospheric flight. First, since the density of water is close to the density of the missile, the inertia of the water displaced can not be neglected in the prediction of

the motion of the missile during the underwater portion of the flight. The inclusion of these water inertia effects increases the apparent mass, inertia and inertial coupling of the vehicle. Second, unlike air, water can change phase if the local static pressure is sufficiently low. The resulting region of cavitation not only alters the flow around the missile, but also, because of

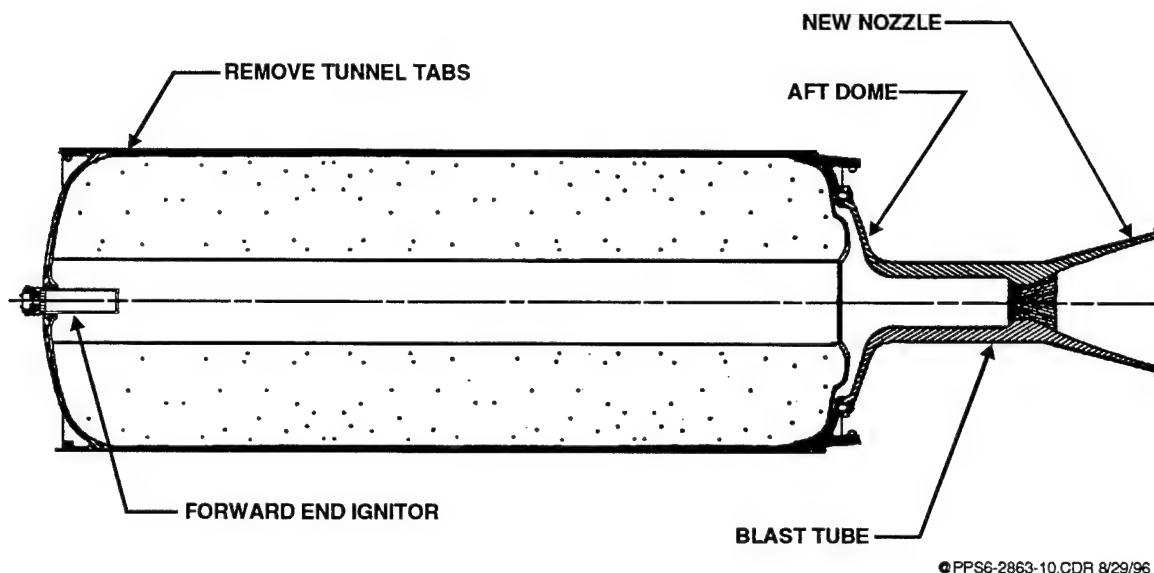


FIGURE 10. PROPULSION SECTION

the unsteady nature of the cavitation region, can potentially lead to local surface erosion and structural damage of the missile.

To ensure that the unique character of underwater flight was properly characterized during the Submarine Launched SLATACMS Feasibility Study, the Navy asked Lockheed Martin Missiles and Space (LMMS) with the assistance of WEC, to evaluate the SLATACMS underwater flight. Both companies have had extensive previous experience with the fleet ballistic missile (FBM) program. During this study, the three potential problem areas examined were: cavitation, underwater deceleration, and underwater stability. The basic results in each of these three areas will be discussed.

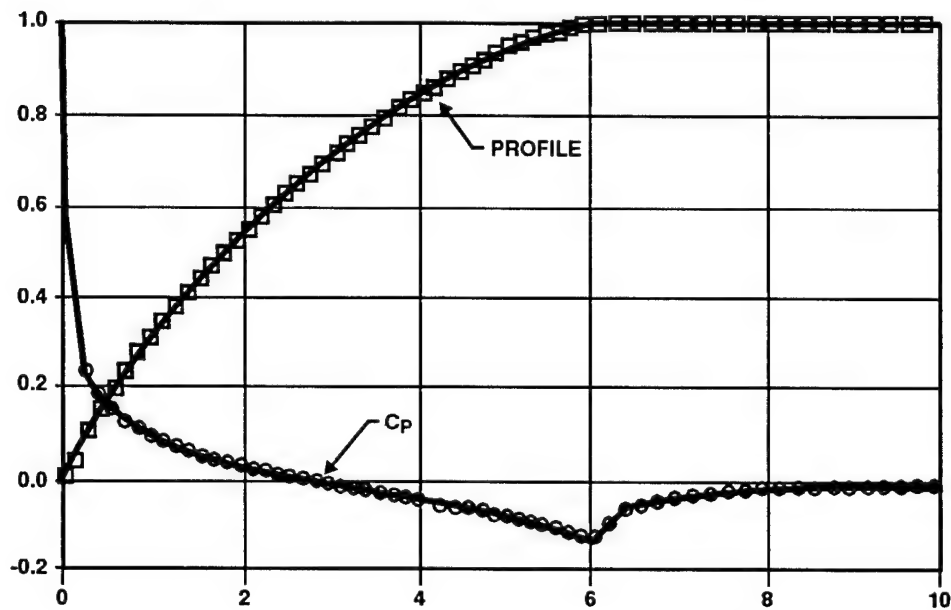
Cavitation

Cavitation occurs when the local static pressure is less than the vapor pressure of the water. The local pressure depends on the missile shape, velocity, and ambient

pressure. The effects of missile shape, expressed in terms of the local pressure coefficient, is only weakly dependent on the depth of the missile below the water surface. The pressure coefficient for the SLATACMS missile was evaluated analytically for zero angle of attack and is shown in Figure 11.

Cavitation, if it occurs, will first occur at the location of the lowest pressure coefficient. For the SLATACMS missile at low angles of attack, the lowest forebody pressure coefficient is at the junction between the von Karman nose and the cylindrical midbody. Because this minimum pressure is negative, the local pressure is below ambient, and for a sufficiently high underwater velocity, the SLATACMS missile will experience cavitation.

While the SLATACMS velocity monotonically decreases between tube exit and broach, the ambient pressure of the water during ascending flight actually drops faster than does the SLATACMS dynamic pressure. Consequently, the portion of the



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FIGURE 11. PRESSURE DISTRIBUTION ON SLATACMS NOSE

underwater trajectory at which cavitation would occur first is near nose broach. The velocity necessary to produce cavitation at nose broach was calculated to be 135 fps. This value exceeds the velocity expected at any time in the underwater flight. It is concluded that if the angle of attack can be kept small, the SLATACMS missile will not experience cavitation problems on the basic missile body.

Underwater Deceleration

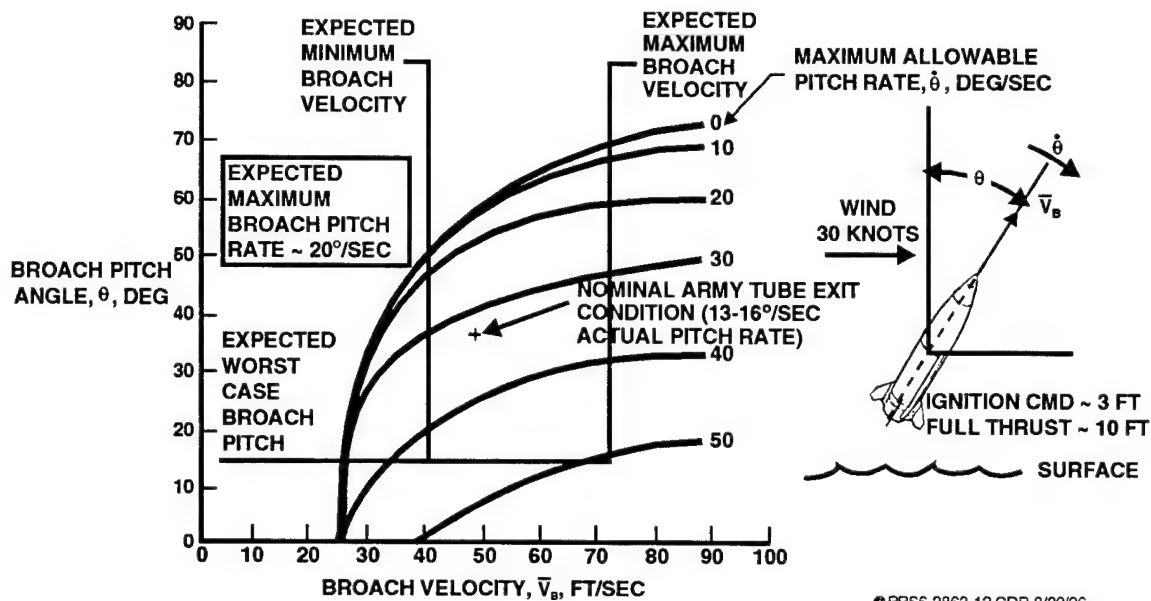
To achieve a satisfactory transition from underwater flight to atmospheric flight, the SLATACMS missile must exit the water with sufficient velocity and with acceptable attitude and body rates.

The envelope of acceptable flight conditions, shown in Figure 12, was determined from a parametric set of trajectories in which the criterion for satisfactory flight capture was that, during capture, the flight path not deviate more than 75° from

the vertical. One of the results of this study was that the missile velocity at broach must be greater than 25 fps regardless of pitch attitude and attitude rate.

The velocity at tube exit is bounded by the capacity of the capsule gas generator. With the missile being nonbuoyant and unpowered during the underwater flight, the requirement of a broach velocity places a potential limit on the launch depth that is dependent on the missile drag coefficient. A significant flow phenomena observed for vertical tube launched underwater missiles is the tendency of a bubble of gas created by the expulsion of the missile from the tube to follow the missile to the surface. By potentially eliminating the base drag normally expected the pressure in this bubble can significantly reduce the missile drag coefficient during the vertical ascent.

For the FBMs, the base bubble is large and near ambient pressure; however, several factors suggest that the SLATACMS base bubble may not be nearly as large as



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FIGURE 12. UNDERWATER SLATACMS LAUNCH BROACH CONDITIONS FOR TRANSITION TO ATMOSPHERIC FLIGHT

that suggested by FBM experience. The two factors currently considered are the small size of the SLATACMS relative to the FBMs, and the low drag shape of the SLATACMS basic body (high fineness ratio nose and boattail). Experience with the Tomahawk missile, which is also much smaller than the FBMs, suggest a much smaller base bubble and higher drag coefficient than predicted, based on FBM experience. Consequently, LMMS feels that because of uncertainty in the base bubble pressure for the SLATACMS missile, some uncertainty in the underwater drag coefficient exists.

To evaluate the sensitivity of acceptable launch depth to drag coefficient, a parametric series of underwater ascents were run. During this study, the actual tube exit velocity variation with launch depth, as estimated by WEC, was considered; however, the value of missile velocity at all tube depths was approximately

80 fps. The results of this series of the parametric drag study are shown in Figure 13.

The current estimate of underwater drag is 0.14. This value is broken down in Table 1 shown below.

TABLE 1 DRAB COEFFICIENT ESTIMATE BREAKDOWN

Skin Friction	0.057
Fin Drag	0.013
Base Drag	0.070
Total	0.140

With the current estimate, the launch depth limit would be 175 feet. Even if the drag coefficient were as much as 0.2, a value derived from full scale Tomahawk tests, the launch depth limit would still be approximately 150 feet. From the drag parametric study, it was concluded that any launch depth limit due to missile

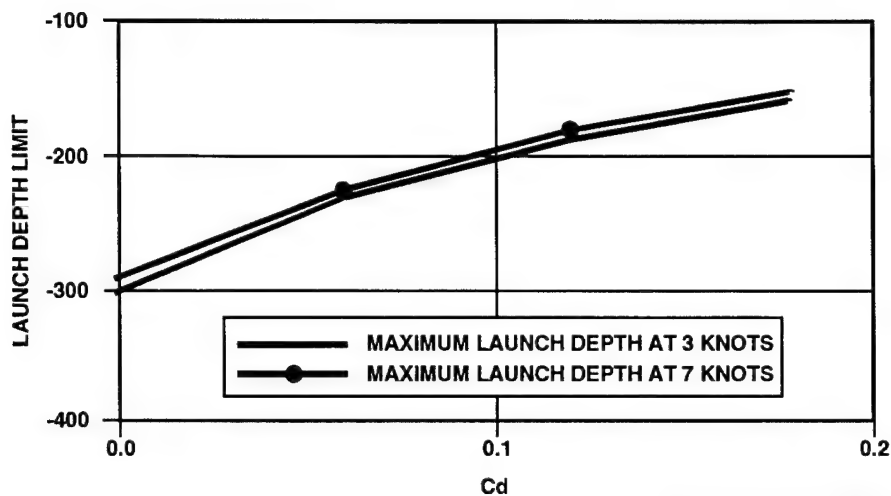


FIGURE 13. MAXIMUM LAUNCH DEPTH VS DRAG COEFFICIENT

underwater deceleration will still result in a significant launch window.

Underwater Stability

Like the FBMs and the Tomahawk missile, the SLATACMS is statically unstable at tube exit. The FBMs and the Tomahawk missile have a thrust vector control system which can limit the pitch excursions of the missile during underwater flight. Because of the similarity in masses, it would be possible to fit a Tomahawk underwater booster to the SLATACMS missile. Underwater trajectory calculations confirmed that a SLATACMS with a Tomahawk underwater booster would be able to satisfactorily transition to atmospheric flight from any point within the launch envelope currently under consideration. FBM experience, however, suggested that from the launch depths considered for SLATACMS deployment, a TVC system might not be needed.

To evaluate the necessity of an under sea control system, two sets of parametric underwater trajectories were performed. The first considered the basic SLATACMS missile with the fins folded, and the second

assumed a set of generic fins (sufficiently large to stabilize the missile under water) were added to the missile base. The study results are shown schematically in Figures 14 and 15 suggest that the launch window for which the unstable missile would satisfactorily transition to atmospheric flight after broach was limited to shallow launches at low to medium cross flow velocity (submarine speed). If the missile was stabilized, however, the trajectory performance without an underwater control system would be satisfactory for any launch depth compatible with the missile deceleration limits discussed in the previous section.

Stability System Design

Initial consideration was given to opening the SLATACMS fins underwater; however, the underwater loads were sufficiently high as to require a significant change in the fin opening concept. The approach taken was to design a cylindrical extension (the length of a Tomahawk booster) capable of housing a separate set of underwater fins. This extension also enclosed the SLATACMS fins resulting in a

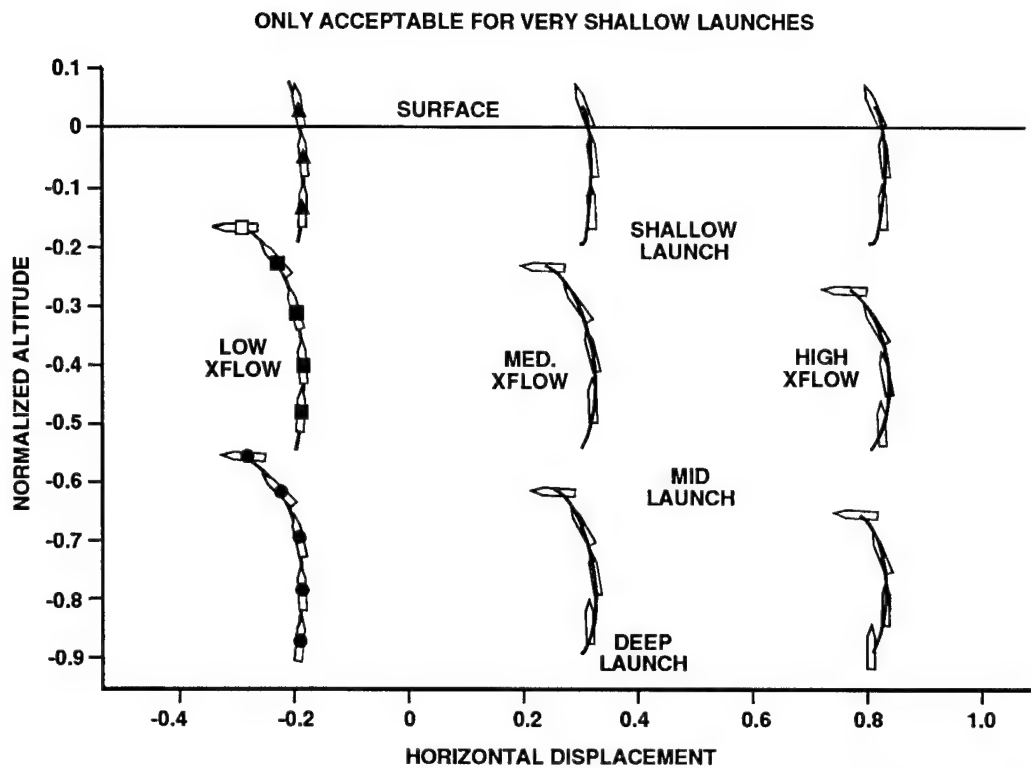


FIGURE 14. WITHOUT FINS

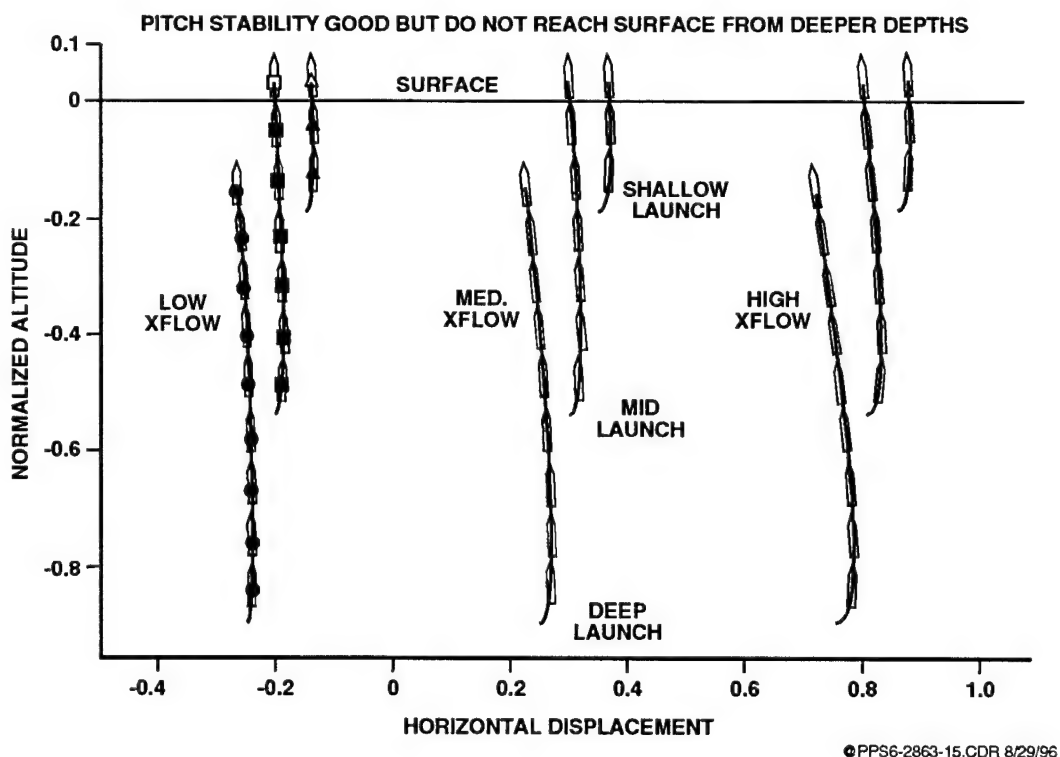
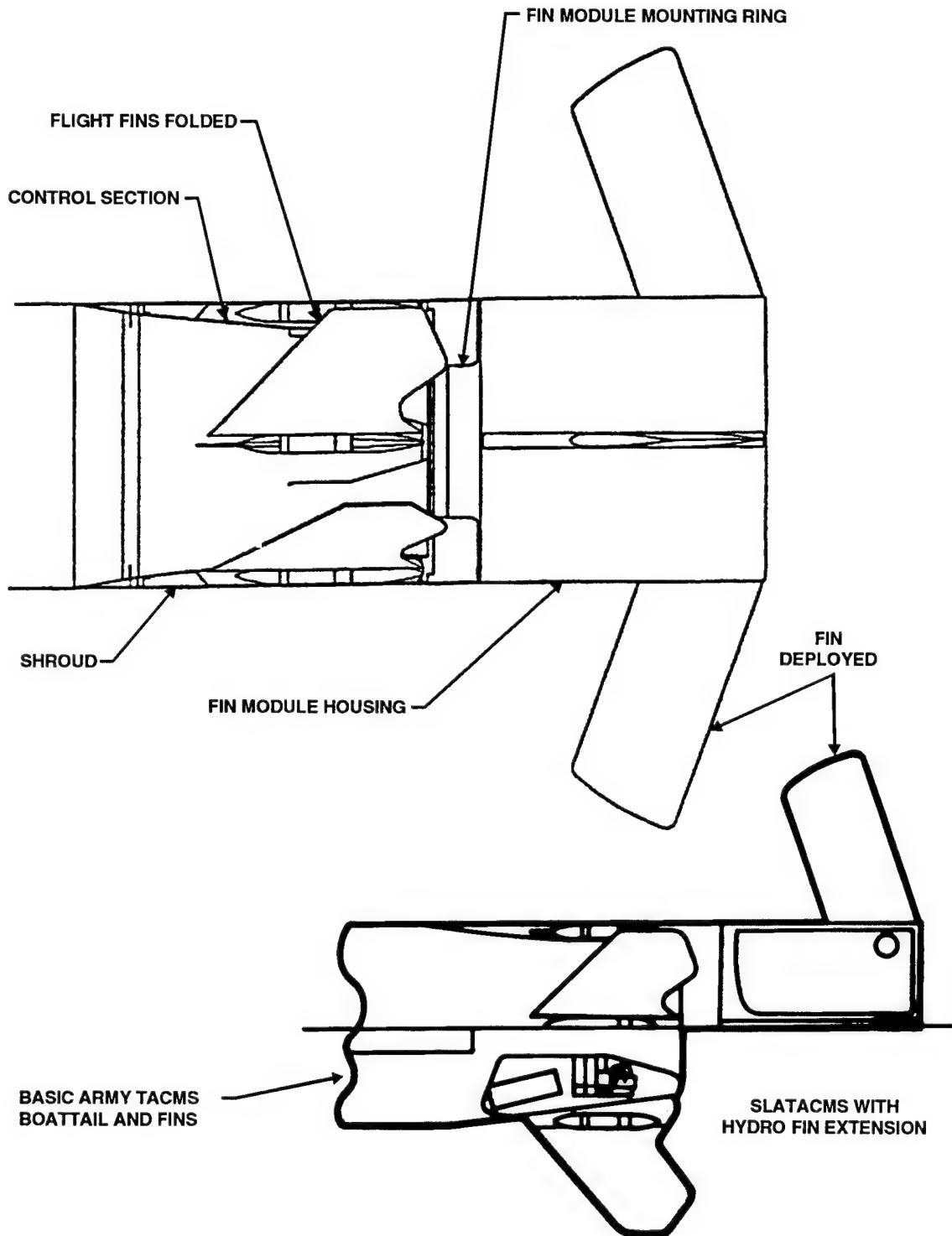


FIGURE 15. WITH FINS

cylindrical afterbody prior to fin deployment. The configuration with the aft extension is compared to the SLATACMS missile in Figure 16. The assembly is

located behind the boattail and functions from ejection from the capsule until broach when it is jettisoned. The module consists of a housing the same diameter as the



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FIGURE 16. STABILIZATION FIN MODULE

missile motor case, 23.9" and 28.67" long. The housing supports and deploys four fins and supports a shroud over the missile flight fins. The stabilization fins will be positioned in line with the centerline of the missile and positioned 45° to the flight fins. The fins are deployed by rotating a hinge point at their aft end. They are fixed and uncontrollable. Each fin has two extension springs that deploy the fin within 100ms. A restraint system is incorporated to delay the fin deployment until after they clear the submarine deck hatch. The shroud will be fabricated in two 180° sections from stainless steel sheet. It will be hinged along its aft edge to the forward end of the module and extend forward to the motor case. Near the forward end, it will engage a latch on the boattail. The shroud retains the flight fins and provides a surface during capsule ejection for the capsule seals with

which to interface. When the module is jettisoned, the shroud panels slide aft, the forward end disengages the boattail latches, and the panels separate from each other but remain secured to the module by the hinges. The flight fins deploy as the shroud separates. The module attaches to the boattail at the forward end with a bolt ring. A severance charge is installed inside the boattail and will cut the module mount for jettison. Integrated assembly of the missile warhead, SRM and aft control section is the same as Block IA, except for the tunnel, fins and added fin module with shroud panels. The current tunnel harness and two piece cover will be replaced with a thin flex ribbon cable bonded directly to the motor case. A stainless steel cover will secure the forward end of the tunnel harness at the warhead motor case joint and provide a cover over the

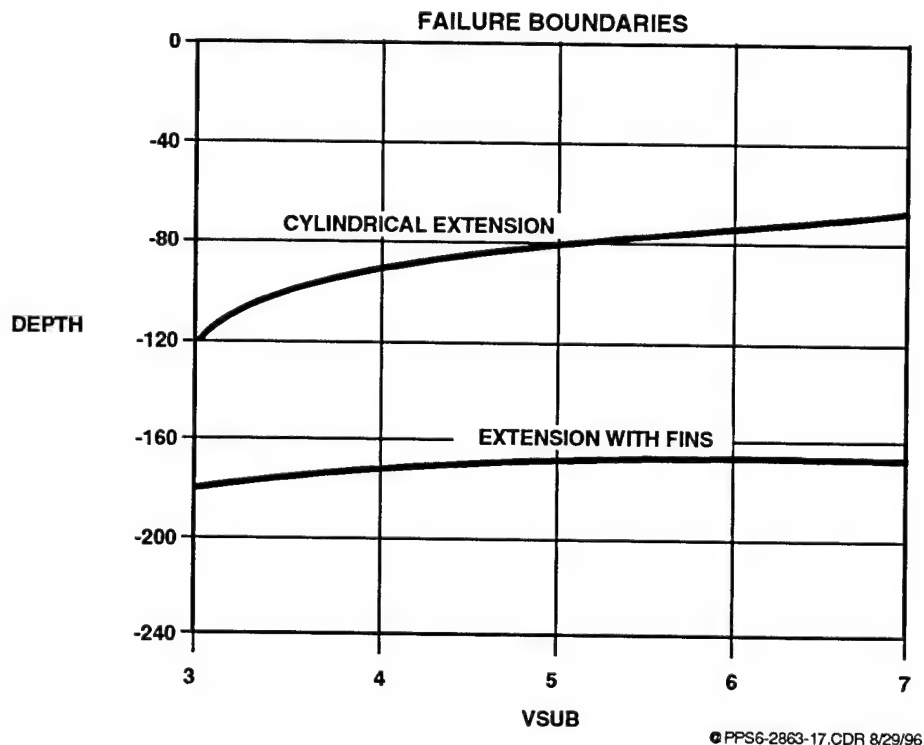


FIGURE 17. LAUNCH WINDOW FOR CYLINDRICAL EXTENSION AND EXTENSION WITH FINS

existing tunnel cutout in the warhead skin. Figure 17 shows the acceptable launch depth versus cross flow velocity for the SLATACMS with aft extension and with hydrodynamic fins both opened and closed. The cylindrical section alone significantly increased the missile damping characteristics, and significantly enlarged the launch window over that of the basic missile. The launch envelope of the SLATACMS with cylindrical extension and hydrodynamic fins is limited only by the missile deceleration characteristics.

GUIDANCE AND NAVIGATION

Surface-to-surface tactical missiles must be able to strike at targets anywhere within the performance envelope of the missile. The missile must engage targets at any range or altitude from minimum to maximum. The guidance scheme must possess sufficient robustness to contend with off-nominal environmental conditions (e.g., atmospheric conditions), in addition to missile conditions such as tip-off, thrust misalignment and motor performance variations.

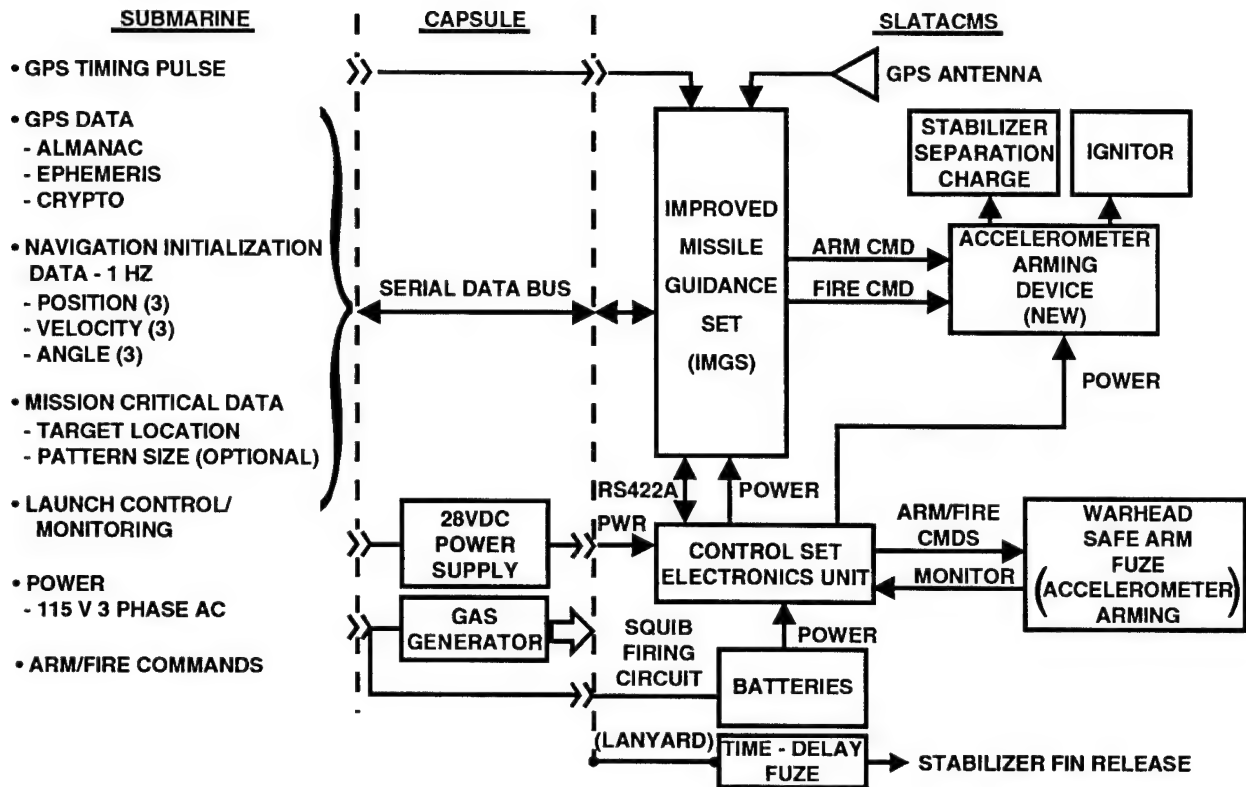
Guidance and navigation for the SLATACMS remain the same as the Army product. Pre-launch functions and fire control system mission initializing are also similar. Power and arm/fire commands are required for the launch capsule gas generator, in addition to pre-launch communications to the missile. The SLATACMS unique command sequence controls the stabilizer fin release, stabilizes separation and motor ignition following broach. Figure 18 shows the electronic interfaces between sub, capsule and missile. An explicit guidance scheme was developed for a semi-ballistic, inertially-guided missile in a surface-to-surface role.

Pre-apogee guidance is basically open loop with respect to target position, and post-apogee guidance is based on Instantaneous Impact Point (IIP) predictions. For target ranges shorter than the natural ballistic range of the missile, the scheme inherently commands the missile to pushover. For longer ranges, commands are generated which force the missile to fly an optimum glide, thereby extending the range. Implementation of the scheme requires neither extensive onboard computational resources nor complicated pre-launch calculations.

GPS NAVIGATION AIDING

The Army TACMS GPS subsystem consists of a GPS antenna, an Embedded GPS Receiver (EGR), and a Navigation and Guidance Computer (NGC). The GPS antenna is built by Ball Antenna and the EGR is a Rockwell Collins GEM-III GPS receiver. Both the EGR and the NGC are enclosed within the IMGS housing and communicate via a Dual Port RAM (DPRAM) interface. Inertial navigation instruments and assembly are supplied by Honeywell, GNO.

The GPS antenna has three antenna beam patterns which can be selected from the NGC. The three patterns are an omnidirectional pattern (Omni mode), an aft steered null pattern (Null Aft mode), and a forward steered null pattern (Null Forward mode). Before the missile has left the missile tube, the Omni mode is selected and the GPS signal rebroadcast into the missile tube is received by the missile's antenna. Once the missile is launched and during the time it is at a high pitch altitude, the Null Aft mode is selected. This Null Aft mode shifts the beam slightly nose forward so that satellite signals near the nose of the



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FIGURE 18. NOTIONAL SLATACMS - ELECTRICAL INTERFACE

missile are not severely attenuated. During the flight, the missile's nose pushes over slowly and a switch is made to the Omni mode. During the terminal phase of the flight, the missile's nose pushes down even further and a final switch is made to the Null Forward mode. This Null Forward mode shifts the beam slightly aft and develops a Null region toward the nose of the missile which attenuates any jamming signals emanated from a target located jammer.

To support a short pre-launch time line, the EGR is 'hot started'. The GPS receiver on the launcher (or XGR for external GPS Receiver) supplies the EGR with sufficient information to allow the EGR to perform a direct acquisition of the P(Y)-code GPS signal allowing it to bypass the C/A-code

GPS signal. Data passed from the XGR to the EGR consists of almost the entire GPS satellite navigation message, which includes 1) ephemeris data for satellites in view of the launcher, 2) almanac data for each satellite in the current constellation, and 3) other Subframe 4 and 5 data pages.

In addition, a string of precise time pulses (accurate to ± 5 msec) and time messages (identifying the times of the pulses) are provided to the EGR from the XGR. Just a single pulse is required to transfer precise time to the EGR. However, due to concerns over long term drift in the EGR's crystal oscillator while the missile was in storage, a string of pulses (3 minimum, 10 desired) is used to calibrate this oscillator.

Other data provided the EGR prior to launch includes the missile's position, antenna masking tables, and GPS cryptographic keys. The missile position data is the same data used to initialize the missile's INS. The antenna masking tables are used by the EGR to determine if acquisition of a particular satellite is likely to succeed based on the missile's body attitude, the satellite's location in the sky, and the antenna beam selected. The GPS cryptographic keys are necessary to track Y-code and remove the effects of selective availability.

After the EGR is initialized, it is placed into the Navigation mode where it performs a direct P(Y)-code acquisition on the rebroadcast GPS satellite signals available in the missile tube. This acquisition normally requires about 12 seconds to complete.

The final GPS subsystem pre-launch activity involves inertially aiding the EGR. Once the missile's INS system is placed into its Navigation mode, data from the INS is provided to the EGR at 10 Hz until the end of the flight. This inertial aiding data (IAD) consists of position, velocity, acceleration, and missile body attitude data. As GPS measurements are used to correct the INS data during the flight, corrected IAD is passed on to the EGR.

The missile is situated at a -90° roll attitude in the missile tube. Thus when the missile exits the tube, the GPS antenna can only see about half the sky. At about 12 seconds, the missile completes a $+90^\circ$ roll maneuver to place the missile's wiring tunnel and GPS antenna on top, and an acquisition reset command is sent to the

EGR to command it to reevaluate its optimum satellite constellation based on its current attitude and antenna beam selection.

A tightly coupled GPS/INS Kalman filter resides in the NGC. This filter consists of eleven error states: 3 position, 3 velocity, 3 attitude, 1 clock bias, & 1 clock drift. This Kalman filter processes the pseudo range measurements from the EGR available once each second. Measurement processing starts no sooner than 30 seconds after launch and continues to the end of the flight. Four measurements (i.e., one measurement from four satellites) are required to start the filter. Once started, this filter will process from 1 to 4 measurements from the EGR. Nominally, four measurements are available each second. The filter solution is allowed to converge before filter data is used to correct the INS. The Kalman filter is declared converged after it has processed 40 GPS measurement, which nominally takes 10 seconds (i.e., 10 seconds times 4 measurements per second). Should GPS measurements stop for any reason, the filter will continue to propagate its error states forward in time.

A feed forward scheme is used to correct the INS data once the GPS/INS Kalman filter has converged. As the INS position and velocity data arrive in the NGC from the Instruments System Computer, it is corrected utilizing data from the filter states. This corrected INS data is then "feed forward" into the missile's guidance routines as well as to the EGR in the form of corrected IAD. Thus the INS system is allowed to navigate without any knowledge of GPS and the EGR is provided the most accurate IAD available.

The INS data is continually corrected at 10 Hz from the time the filter converges to the end of the flight.

Guidance Scheme

The guidance scheme used on TACMS is designed to provide the proper trajectory shaping for all target ranges, from minimum to maximum. It efficiently manages the missile's energy for long range targets while maintaining sufficient flexibility to bleed off excess energy for short range engagements. The trajectory is divided into three phases with each phase having a different guidance law. The initial stages of flight after launch are utilized to orient the missile velocity vector to the proper flight path angle in the pitch plane and to turn the missile toward the target if the missile was launched out-of-plane (i.e., not directly along the azimuth to the target). The guidance scheme utilized for this phase is called Flight Path Steering. Upon completion, transition to Pre-Apogee guidance occurs and remains in effect until apogee. The remainder of the trajectory is flown under the direction of the IIP guidance scheme. The first two phases are designed to establish a trajectory shape that is robust in terms of energy. The IIP phase is designed to guide the missile to the target and, as such, is the only portion of the trajectory that features closed loop (with respect to position) guidance.

The coordinate frame used for guidance calculations is a right-handed Cartesian coordinate system with the origin located at the launch site. The X-axis extends along the azimuth to the target. The Z-axis lies in the vertical plane and is

positive down. The Y-axis is positive to the right (looking downrange from the origin), thereby completing the triad. The target location is specified in this frame.

Flight Path Steering is activated after the initial launch transients have been damped and is active during the first 12 seconds of flight. The purpose of FPS is to steer the missile to the commanded flight path angle in the vertical plane and turn the missile to the target heading. Pitch and yaw flight path angle errors are processed through proportional plus integral controllers to obtain angle-of-attack and sideslip angle commands. These commands are limited and combined with pitch and yaw flight path angles to generate missile body attitude errors. These resulting errors are then fed to the attitude autopilot.

Flight Path Steering is an important segment of the overall guidance scheme. The entire trajectory shape is determined by the performance of this phase. Flight Path Steering must be sufficiently robust to handle all trajectory disturbances (e.g., tip-off, thrust misalignment, winds) and reliably bring the missile to the proper state vector.

The Pre-Apogee guidance law takes over control of the trajectory at the end of the Flight Path Steering phase and continues until the missile reaches apogee. The basic objective of this phase is to place the missile at the proper apogee point within limits so that the IIP guidance law can deliver the missile to the target. The commands take the form of a constant flight path angle rate modified by a flight path angle error signal. The corresponding

vertical planeation command, perpendicular to the velocity vector, is described as follows:

The flight path angle command varies linearly with flight time and, when combined with the flight path angle command used by Flight Path Steering, establishes the 'desired' apogee time. The effect of this feedback term is weakened by command limiting. For most trajectory profiles, the acceleration commands exceed the aerodynamic capability of the missile at higher altitudes where atmospheric density is low. The commands are then limited by angle-of-attack.

At apogee (determined as the time when the vertical velocity component changes sign), guidance commands are calculated by the IIP scheme. An on-board algorithm predicts the ground impact point given a ballistic (i.e., no maneuver accelerations imposed) flight path through the atmosphere using the missile's instantaneous state vector. It consists of a single second-order Runge-Kutta integration step approximately halfway to the impact point, followed by an analytic solution. This prediction provides not only the predicted ballistic impact point but also the Mach number and flight path angle. These parameters are used in the determination of the warhead fuzing point.

Guidance commands are generated based on the error between the IIP and the desired target location:

$$a_{cmd} = K_{IIP} \frac{X_{Error}}{t_{go}^2}$$

Division by the square of time-to-go provides for an effective gain increase as the missile nears the target. A limit is placed on time-to-go so that the command is not diluted for large values of time-to-go.

The IIP guidance law has several basic characteristics. For target ranges shorter than the natural ballistic range of the missile, the scheme inherently commands the missile to pushover. For longer ranges, commands are generated which force the missile to fly an optimum glide, thereby extending the range. Also, since the error term is with respect to a ballistic, or non-accelerated flight path, the commanded accelerations approach zero as the target is approached. The law generates commands that exceed the aerodynamic capabilities of the missile for periods of time for most trajectories. Angle-of-attack limiting is performed in that case.

Angle-of-attack limiting is a key ingredient of the overall TACMS guidance concept. In order to achieve maximum range, the missile must glide at or near the best lift-to-drag ratio after reaching apogee. Whenever the acceleration commands from the IIP guidance law exceed the aerodynamic capability, then the angle-of-attack is limited as follows:

$$\alpha = \alpha_{L/Dmax} + K_{\gamma} (\gamma_{ref} - \gamma)$$

The best glide angle-of-attack is modified by the product of a gain and a flight path 'error', with respect to a reference flight path angle.

The effect of this limiting scheme is to produce a trajectory with a characteristic second apogee occurring at a lower altitude than the first or primary apogee. As the missile continues downrange toward the target and descends to lower altitudes, the commands unsaturate and the missile flies a continually decreasing angle-of-attack profile. As the missile nears the target, the commanded acceleration approaches zero.

Lateral guidance commands for both Pre-Apogee and IIP phases of flight are generated using a Proportional Navigation approach. Commands are based on the line-of-sight rate to the target.

$$\alpha_{cmd} = K_n \dot{\lambda}$$

This scheme does not constrain the missile's approach to the target along a particular azimuth, but rather lets the azimuth transfer to a target path removing initial aim point offsets.

Autopilot

The TACMS autopilot is a classical design that operates in two modes: an attitude mode for the first 12 seconds of flight and an acceleration mode thereafter. The basic design of the autopilot affords sufficient robustness and flexibility for it to fly a wide variety of payloads with a minimum of software modifications. Relatively minor software changes are required to handle wide differences in airframe static stability, from stable to unstable.

The attitude autopilot operates in conjunction with Flight Path Steering. Pitch and yaw attitude errors are fed through proportional plus integral controllers. Angular rate feedback provides the necessary airframe inner loop stability. Compensation is added in the rate loop as required depending upon the characteristics of the payload.

The acceleration autopilot takes over control of the missile after the attitude autopilot and operates in conjunction with the Pre-Apogee and IIP guidance laws. Pitch and yaw acceleration errors are fed through proportional plus integral controllers followed by a first order lag in each axis. Angular rate feedback provides the necessary airframe inner loop stability. Compensation is added in the rate loop as required depending upon the characteristics of the payload.

The roll axis autopilot operates throughout the entire flight. Its purpose is twofold: perform a 90° roll maneuver shortly after launch to orient the missile in the proper roll attitude and to maintain that roll attitude for the remainder of the flight. A proportional plus integral controller is used to nullify the roll attitude error; rate feedback is provided to supply the necessary damping.

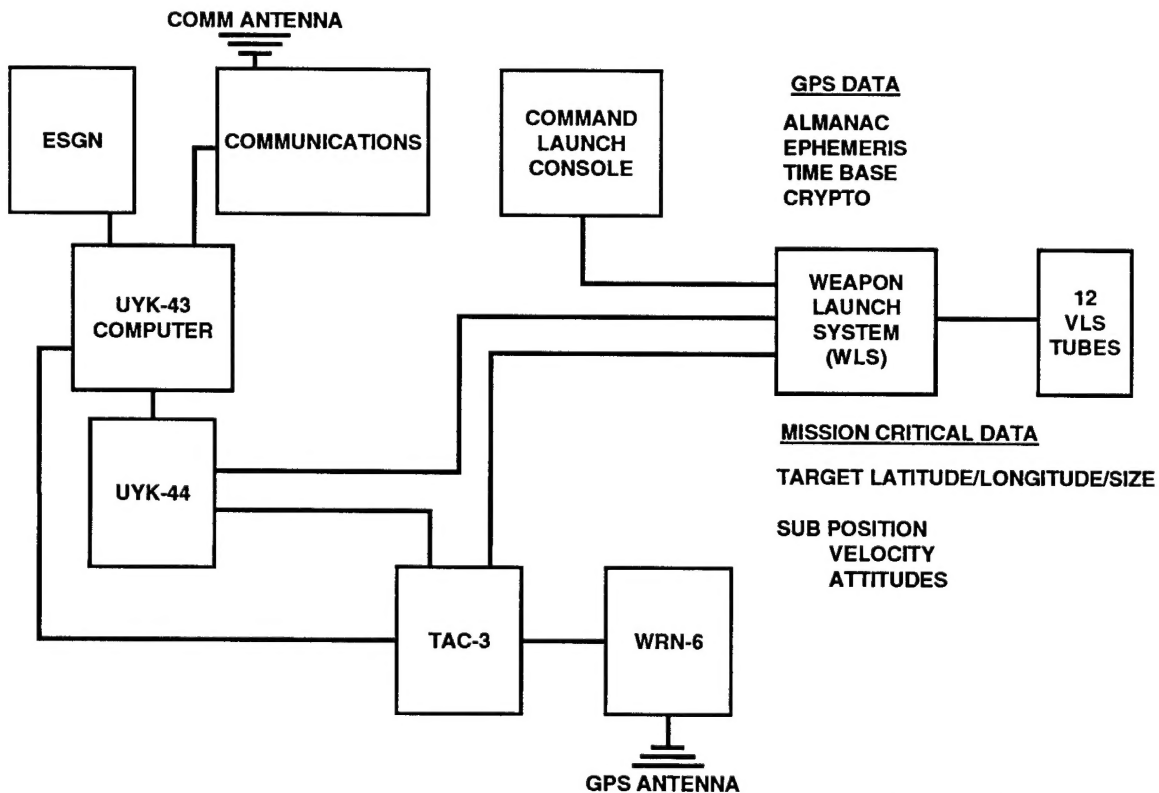
The autopilot calculates three fin commands (roll, pitch, yaw), fed into fin mixer to get the four individual fin commands which are sent to the boattail located control electronics and electro mechanical actuators.

FIRE CONTROL INTERFACE

The SSN688 Weapon Launch System (WLS) will generate the same mission critical data (MCD) the Army M270 launcher does today. MCD data file consists of launch and target latitude/longitude/altitude geodetics. The sea-based launch conditions require velocity states added to missile attitudes for navigator initialization. The submarine navigation system, WRN-6, passes the external GPS (XGR) data, satellite almanac and ephemeris and sub-frame 4&5 CRYPTO data. Fire control general arrangement is shown in Figure 19.

CONCLUSION

The Strategic Systems Programs (SSP) sponsored study showed the feasibility of launching the Army Tactical Missile System from SSN688 class submarines. No 'show stoppers' were discovered during the study. The study was a praiseworthy product of a true integrated product team approach of industry and government. Special credit is due to members from Lockheed Martin, LMMS/Sunnyvale, Northrop-Grumman, WEC/Sunnyvale, and the members of the Navy's SSP.



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FIGURE 19. SSN 688 FIRE CONTROL SYSTEM

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